

SIMPLE ATMOSPHERIC PERTURBATION MODELS FOR SONIC-BOOM-SIGNATURE DISTORTION STUDIES

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INTRODUCTION

Sonic-boom propagation from flight level to ground is influenced by wind and speed-of-sound variations resulting from temperature changes in both the mean atmospheric structure and small-scale perturbations (refs. 1-5). Meteorological behavior generally produces complex combinations of atmospheric perturbations in the form of turbulence, wind shears, up- and downdrafts, and various wave behaviors. Differences between the speed of sound at the ground and at flight level will influence the threshold flight Mach number for which the sonic boom first reaches the ground as well as the width of the resulting sonic-boom carpet (refs. 6-8). Mean atmospheric temperature and wind structure as a function of altitude vary with location and time of year. These average properties of the atmosphere are well-documented (for example, refs. 9 and 10) and have been used in many sonic-boom propagation assessments. In contrast, smaller scale atmospheric perturbations are also known to modulate the shape and amplitude of sonic-boom signatures reaching the ground, but specific perturbation models have not been established for evaluating their effects on sonic-boom propagation. The purpose of this paper is to present simple examples of atmospheric vertical temperature gradients, wind shears, and wave motions that can guide preliminary assessments of nonturbulent atmospheric perturbation effects on sonic-boom propagation to the ground. The use of simple discrete atmospheric perturbation structures can facilitate the interpretation of the resulting sonic-boom propagation anomalies as well as intercomparisons among varied flight conditions and propagation models.

Outline

- **Introduction**
 - **Example atmospheric profile**
 - **Wind shear probabilities**
 - **Temperature gradient statistics**
 - **Single mode wave model**
 - **Closing remarks**

INTRODUCTION (cont'd.)

An observed atmospheric profile is used to illustrate discrete atmospheric layers with strong wind shear and high-temperature gradient values. Statistics for vertical wind shears measured by FPS-16 radar tracking Jimsphere balloons and by the conventional upper-air rawinsonde measurements (refs. 10–14) are presented. These wind statistics and data for vertical temperature gradients in the lower stratosphere also indicate the magnitudes of nonturbulent atmospheric perturbations that may be of concern to sonic-boom propagation studies. Turbulent eddies at the Earth boundary layer distort the sonic-boom overpressure time history signature arriving at the ground. Distortions produced by turbulent layers far from the ground will tend to return to an undistorted N-wave shape signature before reaching the ground. Larger scale wind shears, temperature gradients, and oscillatory activity, such as mountain waves and other atmospheric wave motions, may act like airplane maneuvers to modulate sonic-boom signatures over distances of a few miles as a result of focusing boom overpressure into strong and weak regions.

Waves are induced by flow over topographic or cloud barriers and their effects are often visible in the resulting cloud patterns. Wave phenomena have received much qualitative attention in both observation and analysis (refs. 15–17). However, very little statistical documentation exists to quantify their intensity, and computational methods have only recently shown the capability to realistically handle wave behavior. A particular atmospheric gravity wave model, consisting of a solitary wave mode (ref. 18), is proposed here for initial evaluation of nonturbulent atmospheric perturbation effects on sonic-boom signatures at ground level. Such a model incorporates realistic combinations of vertical and horizontal wind disturbances with their attending temperature or density variations. It also approximates the real atmosphere for cases in which a succession of wave crest cloud lines are observed downwind of mountains or islands.

Influence of Atmospheric Variations on Sonic Booms

- **Mean wind and temperature profiles determine**
 - **Threshold Mach number**
 - **Boom carpet**
 - **Intensity effects**
- **Small scale turbulence distorts signatures**
- **Greater "healing" distances required for quasi-stationary gradients and wave motions**
- **Assessment of effects on conventional and "shaped" signatures can be facilitated by use of discrete models and field measurements**

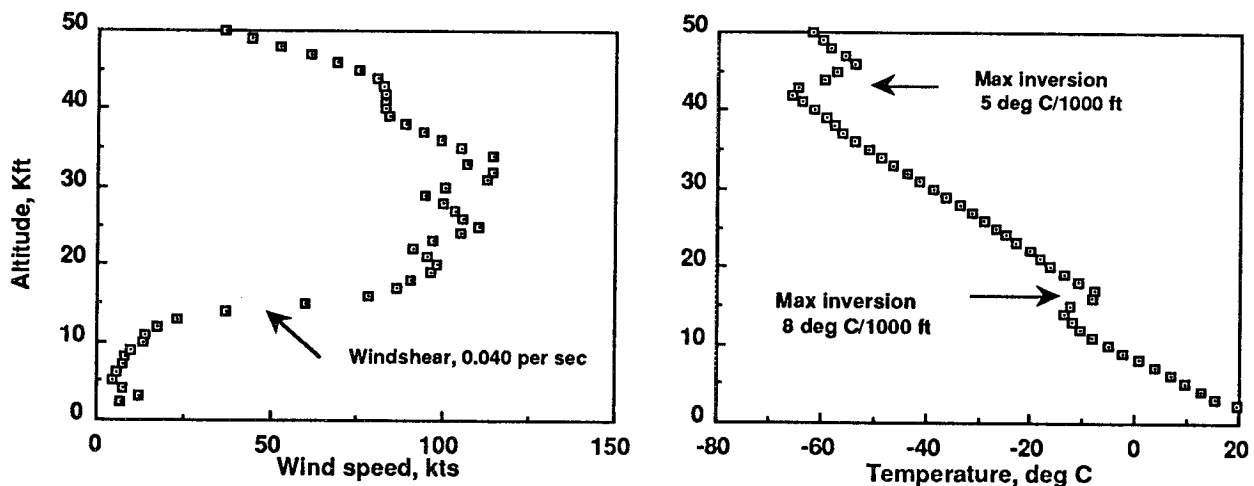
REAL-DAY ATMOSPHERIC PROFILE EXAMPLE

Strong weather fronts and jet-stream activity induce large temperature gradients and wind shears in the atmosphere. Horizontal temperature gradients tend to be in balance with vertical wind shears, and stable vertical temperature stratification tends to preserve wind-shear layers. Stable stratifications occur when the decrease in temperature with altitude (lapse) is less than that associated with an adiabatic process following the decrease in pressure with altitude. Thus, isothermal layers and inversion layers (where temperature actually increases with altitude) provide static stability that tends to maintain wind-shear layers. As the sonic boom propagates through the atmosphere, nonuniform changes in the speed of sound along the shock front bend the direction of propagation to produce focusing effects. Propagation speeds change directly with wind or air motion changes and with temperature. A 1-percent change in the speed of sound will be experienced for a temperature change of approximately 5°C .

The figure below illustrates a case (April 10, 1994, Edwards CA) with both strong wind shear in a mid-tropospheric stable layer and a strong temperature inversion above the tropopause. Windspeeds increase from 23 knots at 13,000-ft altitude to more than 78 knots at 16,000 ft and reach peak speeds of 98, 110, and 114 knots at altitudes of 20,000, 25,000, and 34,000 ft, respectively. The vector wind shear, given by the wind vector change divided by the altitude interval over which the change takes place, reaches a maximum of $0.040/\text{sec}$ at 15,000 ft. Temperature is nearly constant or increasing with altitude between 13,300 and 16,500 ft. The vertical temperature gradient or inversion rate reaches a maximum of $+8^{\circ}\text{C}/1000\text{ ft}$ between 15,400 and 15,800 ft.

Above the tropopause, which is marked by a minimum temperature of -66.3°C at 42,350 ft, the temperature increases to -52.3°C at 45,760 ft. The overall inversion rate for the 12.5°C temperature change in this layer is $3.6^{\circ}\text{C}/1000\text{ ft}$. A maximum rate of about $5^{\circ}\text{C}/1000\text{ ft}$ is observed between 43,000- and 44,000-ft altitude. The windspeeds begin a marked decrease with altitude above the tropopause.

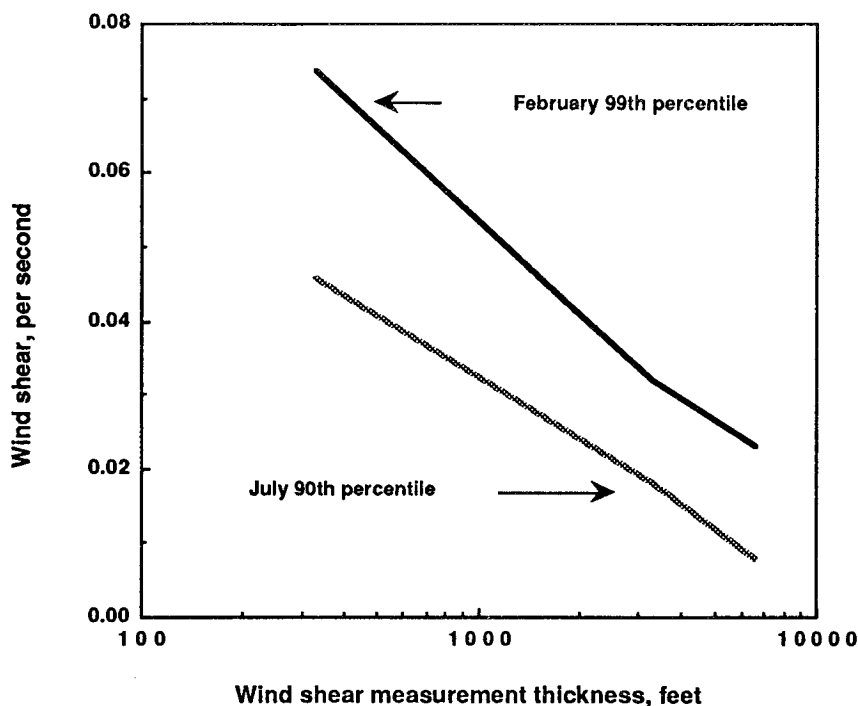
Edwards Wind and Temperature Profile April 10, 1994



WIND SHEAR PROBABILITIES

Measured wind-shear magnitudes depend on the depth of the layer over which the shear is measured. Detailed wind-shear observations and their statistical analyses for altitudes below 60,000 ft have been abundant since the initiation of the manned Space Program. These observations have used special balloons (Jimspheres) tracked by FPS-16 radar to altitudes near 60,000 ft and conventional weather balloons to altitudes of about 100,000 ft. Jimsphere wind data studies accomplished by the NASA Marshall Space Flight Center (refs. 10-13) have provided a wealth of information on wind changes and wind shears and on the relationship between wind shear and the thickness of the altitude layer over which the shear is measured. Wind shear is measured to a reasonable accuracy over layers thicker than about 300 ft by the Jimsphere and over layers greater than about 2000-ft thick by rawinsonde balloons used for routine upper-air weather observations (ref. 12). Selected data shown below illustrate the variation of the measured wind shear as a function of the altitude thickness over which the shear is measured. To bracket a range of stronger shear values, the figure illustrates a 90-percentile curve for July, when wind shears are weaker, and a 99-percentile curve for February, when they are stronger. Wind shears exceed the values shown by these curves for 10 and 1 percent, respectively, of the observations. For convenience of application, wind shear in units of speed change per unit altitude distance can simply be expressed in units of inverse seconds (or per second).

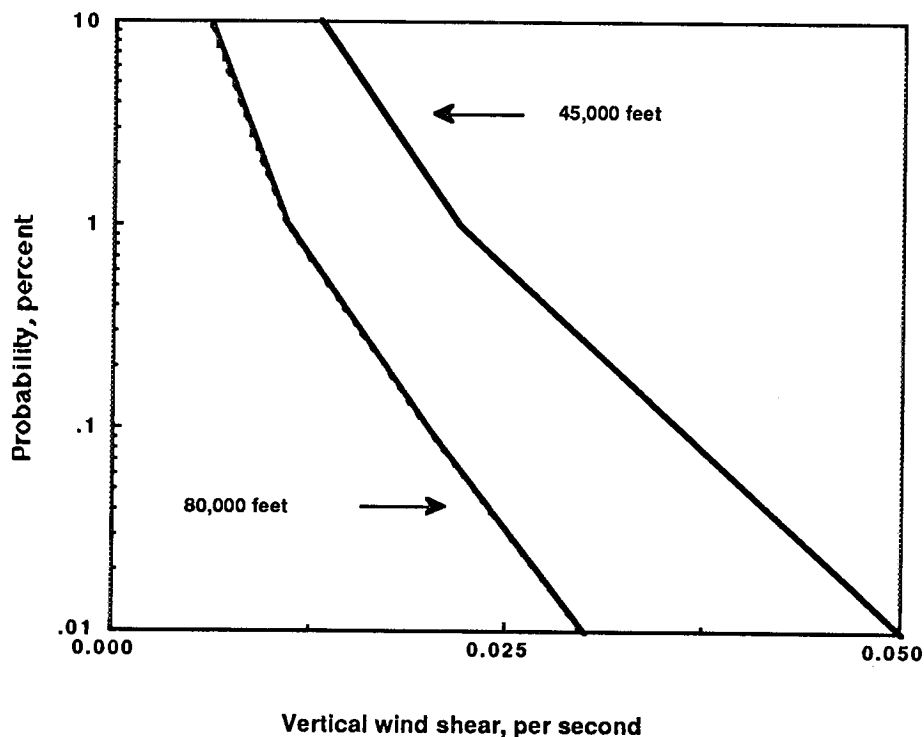
Jimsphere Vertical Wind Shear vs Measurement Thickness for Two Probabilities



WIND SHEAR PROBABILITIES (cont'd.)

Wind shears measured over large altitude distances (or thickness scales) have a positive correlation with windspeed and therefore tend to decrease from a maximum near jet stream altitudes to minimum shear magnitudes in the middle stratosphere, just above supersonic cruise altitudes. This decrease in wind-shear magnitudes in the lower stratosphere is depicted below by curves extracted from rawinsonde data for altitudes of 45,000 and 80,000 ft (ref. 14). Based on these data the maximum shear magnitude measured in the real-day example profile (shown previously) is indicated to be beyond the 99.9-percentile value.

Example Maximum Vertical Wind Shear Probability from Rawinsonde Measurements



STRATOSPHERIC TEMPERATURE GRADIENT STATISTICS

Because the speed of sound in air is a direct function of ambient temperature, the sonic-boom propagation direction will bend when strong temperature gradients are traversed at an oblique angle. The strongest gradients are associated with inversion layers in the lower stratosphere. Statistical analyses of temperature gradient features have not been nearly as adequate as for windspeed and wind shear. Reference 14 reports on an examination of a limited amount of rawinsonde data for (a) strong lapse rates (temperature decrease with altitude) or (b) strong inversion rates (temperature increase with altitude) within layers surrounding the mandatory meteorological reporting levels. This study was motivated to improve the knowledge of probabilities for features associated with high-altitude turbulence experienced by supersonic cruise aircraft. Values depicting the 1.0-, 0.1-, and 0.01-percentile extremes for these data are shown below.

Note that in the lower stratosphere the magnitudes for the decreasing gradients are not as large as those for the increasing temperature gradients. At both the 0.1- and 0.01-percentile frequency of occurrence the decreasing temperature with altitude exceeds the adiabatic lapse rate ($3^{\circ}\text{C}/1000\text{ ft}$), presumably as a result of measurement error in some cases and strong atmospheric dynamics in others. The increasing temperature gradient at 0.01 percentile rate, $24^{\circ}\text{C}/1000\text{ ft}$, is comparable to a density departure rate of approximately 10 percent/1000 ft from the standard day atmosphere, as well as to the speed of sound changing by 5 percent/1000 ft from the standard atmosphere values.

Maximum Temperature Gradients Within Layer for Selected Probabilities

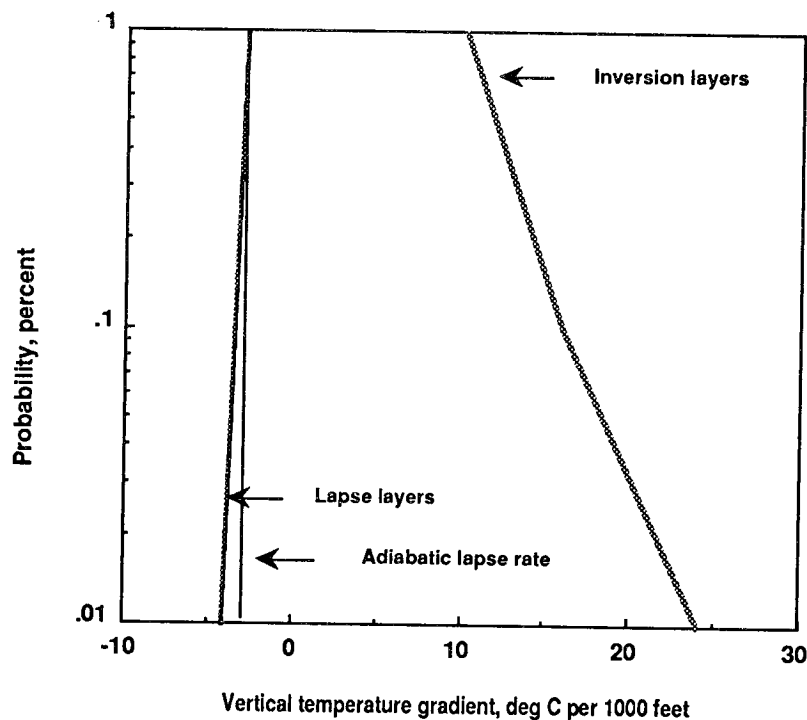
Frequency exceeded	1.0 % ile	0.1% ile	0.01 % ile
Decreasing temperature gradient, $^{\circ}\text{C}/1000\text{ ft}$	-2.9	-3.6	-4.2
Increasing temperature gradient, $^{\circ}\text{C}/1000\text{ ft}$	10	16	24
Temperature increase, $^{\circ}\text{C}$	8	10	12
Nominal thickness, ft for gradients above $5^{\circ}\text{C}/1000\text{ ft}$	1000	2000	3000
Nominal thickness, ft for ΔT above 5.0°C	1600	1000	500

STRATOSPHERIC TEMPERATURE GRADIENT STATISTICS (cont'd.)

As indicated by the data in the previous figure, temperature increases of more than 10°C occur at a 0.1-percentile rate. Inversion rates of $5^{\circ}\text{C}/1000\text{ ft}$ extend over layer depths of 3000 ft at a 0.01-percentile rate of occurrence. A reciprocal situation, temperature changes of 5°C (or greater) occurs over layer thicknesses of less than 500 ft, also at the 0.01-percentile rate of occurrence. Probability curves for the lapse (decreasing with altitude) and inversion (increasing with altitude) temperature gradients within layers of the lower stratosphere are shown in the figure below.

At times, strong inversion layers are located both above and below strong decreasing temperature (lapse) layers in the lower stratosphere. The occurrence of these strong vertical temperature gradients exhibits seasonal dependence and indicates some conditional association with high jet stream windspeeds and strong lower altitude wind-shear layers. These data indicate that lapse rates in the lower stratosphere equal or exceed the dry adiabatic and that inversion rates may exceed $10^{\circ}\text{C}/1000\text{ ft}$ with overall changes of more than 10°C . In summary, strong inversions can increase the speed of sound by more than 2 percent in relatively shallow inversion layers. Depending on wind and flight headings, temperature and wind effects may combine to change the speed of sound by nearly 5 percent across layers of 1000 ft and thicker.

Probability of Maximum Temperature Gradient within Layer



SINGLE-WAVELENGTH WAVE MODEL

Atmospheric vertical motion perturbations are subject to wave behavior nearly all the time except when the vertical temperature profile does not provide static stability. The resulting wave behavior can exhibit multiple modes or wavelengths with both modes and amplitudes changing drastically from one altitude layer to another (see outline below). Strong gravity wave motions are experienced in both the troposphere and at proposed high-speed civil transport (HSCT) cruise altitudes in the stratosphere resulting from dynamic excitation of interactions between the force of gravity and atmospheric buoyancy. Resonant interactions are generally possible at all times when the temperature decrease with altitude is not adiabatic or superadiabatic. Under favored structures of the wind and temperature profiles, barriers to the flow, such as mountains or vigorous cumulus cloud lines, and jet stream oscillations can trigger wave motions in which the resulting vertical motions can be intense and wave amplitudes can be quite large. Such behavior, with complex upstream atmospheric structure, is often beyond solution by classical mathematical analysis.

Initial analyses of the effects of gravity wave motions on sonic-boom propagation for various flight altitudes and trajectories could be overly complicated by the presence of multiple wave modes interacting in an atmospheric structure, which changes markedly from one altitude layer to another. These complications for initial studies of wave effects on boom propagation and focusing can be alleviated by either of two restrictions.

Attributes of Atmospheric Gravity Wave Behavior

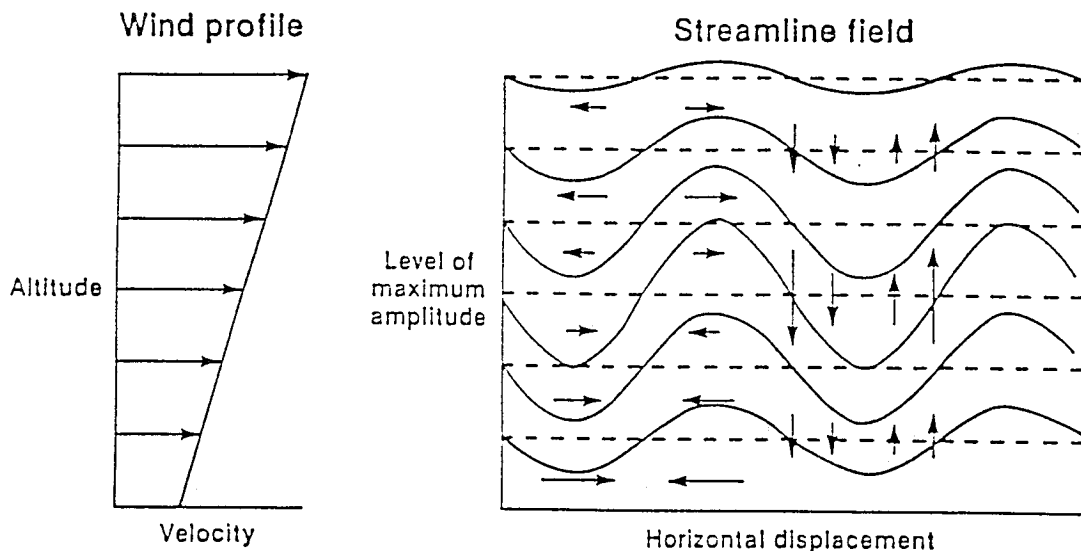
- **Motion perturbations result from interaction between**
 - **Wind profile characteristics**
 - **Presence of flow barriers**
 - **Temperature profile stability or buoyance effects**
- **Wavelength distances between 5 and 50 miles are often observed**
- **Large wave amplitudes occur over the full HSCT altitude range**
- **Dominant wavelengths generally change with altitude**
- **Analytical and numerical treatment of 2-D wave behavior is**
 - **Fairly extensive and maturing**
 - **Lacking in field observation validation**
- **Realistic, simplified representations of wave behavior in the troposphere and lower stratosphere can be generated**

SINGLE-WAVELENGTH WAVE MODEL (cont'd.)

One method is to restrict attention to two-dimensional wave cases that produce high-amplitude perturbations for only one or one-and-a-half wavelengths. Another means of simplification is to restrict attention to two-dimensional wave cases that produce a single-mode (i.e., single-wavelength) trapped wave. This second simplification is believed of more general interest and is described below.

The schematic below shows a two-dimensional trapped, single-mode wave to illustrate the variation of wave induced motion perturbations in the various wave sectors. The wave is produced by a numerical simulation (ref. 18) using an analytically selected upstream profile with constant shear (depicted on the left) and stability (i.e., constant lapse rate). Flow following the streamlines experiences the greatest vertical motion perturbations at the altitude of maximum wave amplitude and at inflection points between troughs and crests. Vectors (not to scale) show downward perturbation velocities from the crest to the trough and upward velocities from the trough to the crest. Temperature perturbations also reach their greatest amplitudes at the altitude of maximum wave amplitude. Temperature increases (warming) occur in the troughs where the air has descended to higher pressures with adiabatic heating; temperature decreases (cooling) occur in the crests where the air has ascended from its upstream altitude level. Horizontal wind perturbation vectors (not to scale) show that the wave dynamics increase horizontal windspeeds in the lower section of the troughs and the upper sections of the crests. Horizontal speeds are reduced in the upper section of the troughs, where the wave amplitude decreases with altitude, and in the lower section of the crests, where rotors with reverse flow near the ground are sometimes created.

Gravity Wave Schematic with Wave-Induced Perturbation Velocity Components



MODEL WAVE INTENSITIES

Selected barrier conditions and atmospheric structure were used to produce a single-mode wave, as described above, by both analytical solution and numerical simulation (ref. 18, Case II). This case generated a nominal intensity wave using a barrier height of approximately 1600 ft in a wind of 20 knots at the base altitude and increasing a modest 2 knots/1000-ft altitude. The temperature lapse rate was 2.25 °C/1000 ft, fairly typical of the lower troposphere and near the standard atmosphere value of about 2 °C/1000 ft. Maximum wave amplitude is attained at an altitude near 10,000 ft, where the stream function's trough-to-crest height change is approximately 4600 ft and the temperature change from trough to crest is about 3 °C. At 10,000-ft altitude the upstream windspeed is about 40 knots, and a wavelength of about 11 nmi prevails throughout the wave pattern. Horizontal windspeed varies by 16 knots from maximum to minimum at the surface and 3 to 4 knots at 15,000-ft altitude. The maximum up- and downdraft velocities are approximately 8 ft/sec. Strength of this wave would be subjectively rated as light or weak, on the basis of the induced vertical velocity and its limited extent above the barrier height. Its amplitude and wavelength are fairly representative of extended (or trapped) wave conditions in which several lines of crest clouds are observed downstream of flow barriers. A stronger wave case, in which the maximum vertical velocity is greater by a factor of at least 3, should also be used in boom propagation studies to encompass a large portion of likely wave amplitudes.

Strong temperature gradients and wind shears are generated locally within the wave structure. The boom propagation effects of similar strength shears and gradients in quasi-continuous layers should be compared with the wave cases to delineate the added focusing effects of vertical motion and wave shape. Layer slopes with respect to flightpath could be varied to cover the range experienced in the wave structures. Based on climatology and clear air turbulence experience, intensities of wind shear used for boom propagation studies should range from less than 0.010/sec (light) to more than 0.020/sec (strong). A realistic range for temperature gradients, which could combine with the wind shear, is from -3 °C/1000 ft to more than +10 °C/1000 ft.

An Approach for the Study of Boom Propagation through Atmospheric Waves

- **Lower- and mid-tropospheric wave cases**
 - Two representative wave intensities or amplitudes
 - Flight altitudes from level of max amplitude to cruise
 - Mach range at each altitude to cover most aircraft types
- **Upper-troposphere wave cases**
 - Two wave intensities and flight conditions varied as above
 - Limit altitude band of wave excitation
 - Use both up- and down-wind headings
- **Lower-stratosphere wave cases**
 - More cases to cover greater range of wind and temperature profiles
 - Two wave intensities and flight conditions varied as above

MODEL WAVE INTENSITIES (cont'd.)

Variables in the boom-propagation study will include flight altitude and Mach number as well as the wave models. Suggestions for the scope of conditions to be studied are listed below. The generation of simple, yet realistic, wave models in the upper troposphere and lower stratosphere will require added consideration of the input barrier and atmospheric structure.

CLOSING REMARKS

Atmospheric gradients and wave motions can affect sonic-boom propagation. Simple, discrete examples that can guide studies of boom propagation have been described in this paper. The specification of wave cases for boom work should initially avoid the potential complexities that could result from variation of wave amplitude and wavelength from one altitude layer to another. It is recommended that initial studies of boom propagation through wave perturbations be attended by propagation cases through similar-strength stratified layers that slope in relation to the flightpath.

- **Sonic boom propagation is subject to atmospheric turbulence, gradients and waves**
- **Complex atmospheric wave behavior can easily complicate boom propagation studies**
- **Realistic simplifications of wave behavior will facilitate the interpretation of boom propagation study results**
- **Comparison of wave induced boom focusing effects with those from stratified gradients of similar intensity is recommended**

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